N-7823/

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA. CALIFORNIA

(NASA CR-52248 ; *505* External Publication No. 808) / N-78231) [note only]

EXTRATERRESTRIAL RADIO TRACKING

AND COMMUNICATION 2 External Publication

M. H. Brockman
H. R. Buchanan
R. L. Choate   and
L. R. Malling

Copy No._____
This document consists of
cover and 45 leaves

45 PAGES

CONTENTS

TABLES

FIGURES

ACKNOWLEDGEMENTS

The authors wish to acknowledge the efforts of all the Jet Propulsion Laboratory personnel whose teamwork contributed to successful radiofrequency tracking and communication with the Pioneer III and IV space probes.   They wish to express particular thanks to Dr. E. Rechtin and W. K. Victor of JPL under whose direction this effort was accomplished.   Acknowledgement is also made to the Collins Radio Company, Cedar Rapids, Iowa, who provided assistance during the design, construction and installation of the Goldstone radio tracking system.

External Publication No. 808

EXTRATERRESTRIAL RADIO TRACKING AND COMMUNICATIONS[1]

M. H. Brockman, H. R. Buchanan, R. L. Choate and L. R. Malling

Jet Propulsion Laboratory
Pasadena, California

ABSTRACT

When the U. S. Army lunar probe program was initiated in 1958, the Jet Propulsion Laboratory was assigned the responsibility for the upper rocket stages and the payload. Payload responsibility included radio tracking and communication with the lunar probe.

The Laboratory's Microlock system, used for communicating with the early Explorer satellites, did not have sufficient range to perform this mission. Therefore, a new radio system designated TRAC(E) -- TRacking And Communication (Extraterrestrial)-- was designed. To the best knowledge of the authors, TRAC(E) is the first deep-space communication link to provide accurate tracking and telemetry data at lunar distances.

The design principles of the TRAC(E) system are presented in this paper in conjunction with a description of the equipment and actual performance data taken during the Pioneer IV lunar mission in March, 1959. TRAC(E) is an integral part of the NASA/JPL radio tracking station located near Goldstone Lake, north of Barstow, California.

Future plans for improving the performance of the (TRAC(E) system
are indicated.

I. INTRODUCTION

The TRAC(E)--TRacking And Communication (Extraterrestrial)--system
is a versatile space-communications system which is capable of communicating
with and tracking Earth satellites, lunar vehicles, or space probes. Two major
questions which had to be answered in the design of such a communications
system for extreme range applications were: What is the operating frequency?
What is the size of the ground antenna? The ground antenna is considered in
a separate report (Ref. 1); the factors which determine the operating frequency
of the TRAC(E) system are outlined herein.

The transmitter in the space probe produces a signal power P_t limited
by the efficiency of the transmitter and the weight of the vehicle electrical
power supply. This power is beamed in the direction of the Earth-based
receiver to provide an effective signal-power gain G_t relative to radiation
uniformly into space. The amount of beaming that can be realized is limited
by the accuracy with which the vehicle's antenna can be pointed and/or the
vehicle's attitude can be controlled. Since the feasibility of vehicle-borne
directional antennas for space communications has not yet been demonstrated,
present vehicle antennas are gain-limited. Therefore, the signal power P_r
received by an Earth-based station is given by

$$P_r = P_t G_t A_r / 4\pi R^2 \tag{1}$$

The term R represents the distance between the space vehicle and the Earth-based station. The Earth-based antenna is assumed to be area-limited (Ref. 1). Examination of Eq. (1) reveals that the received power is independent of frequency to a first order at least.

The choice of the operating frequency can be narrowed somewhat by choosing frequencies which are not seriously affected by the ionosphere (above 100 Mc) nor by the atmosphere (below about 10,000 Mc). With regard to interference, virtually every known source of radio interference decreases with increasing frequency. Of particular importance to space communications is the decrease in brightness temperature of the galaxy with frequency. The largest source of galactic interference lies along the Milky Way or galactic center in a band approximately 15 deg wide, lying near the possible destination and orbits of space vehicles. Reduction in this interference can be accomplished by using antennas with relatively narrow beamwidths operating at the highest frequency that is practical.

In view of the factors considered above, the optimum communication frequency was actually determined by such factors as vehicle-transmitter efficiency and ground-receiver sensitivity--that is, state-of-the-art considerations. Within the time scale of the U. S. Army lunar-probe program (subsequently transferred to the National Aeronautics and Space Administration) and the weight limitations of the Pioneer III and IV lunar probes, development of an efficient stable transmitter in the 1000 Mc range appeared feasible. An operating frequency of 960.05 Mc was eventually chosen.

The TRAC(E) design is based upon phase-lock techniques which have been under continuing investigation and development at the Jet Propulsion Laboratory (JPL) since 1953 (Ref. 2-5). The technique, used by JPL in the Microlock system (Ref. 6), permits use of receiver bandwidths significantly smaller than the magnitude of the doppler shift expected from space vehicles, and proper addition of a limiter provides nearly optimum performance over a wide dynamic range of both signal and interference levels (Ref. 3). Telemetry subcarrier modulation frequencies are synchronously detected, and the basic information is available at the output of phase-locked FM discriminators.

II. TRAC(E) SYSTEM FOR PIONEER III AND IV

Figure 1 is a functional block diagram showing the TRAC(E) system as it was originally designed for tracking and communicating with the Pioneer III and IV probes. In the probe transmitter, the 40.0021 Mc crystal-controlled-oscillator signal is phase-modulated with telemetry subcarriers which contain the measured data as frequency modulation. The resulting phase-modulated signal is frequency-multiplied by a factor of 24 and amplified to provide a 960.05 Mc signal to the probe antenna. The transmitter signal output, normalized to unity, is

$$\text{Cos}\left[24\omega_c t + s(t)\right] \tag{2}$$

where $s(t)$ is the composite phase-modulation signal.

The TRAC(E) receiver is a narrow-band phase-coherent double-conversion super-heterodyne which employs three balanced mixers at 960 Mc, three balanced detectors at 30 Mc, and four synchronous detectors at 455 Kc. The mixers and detectors are three-terminal devices having an input, a coherent reference and an output, and they perform the analytic function of multiplying the waveform of the input signal by the waveform of the reference. These devices in conjunction with three 30-Mc IF preamplifiers, three 455-Kc IF amplifiers, and the voltage-controlled local oscillator comprise the major portion of the ground receiving system. They are arranged in such a manner as to function as the differencing elements of four highly accurate servo systems: (1) the RF servo loop at 960 Mc, (2) the AGC loop, (3) the declination servo-mechanism and (4) the hour-angle servomechanism.

The received signal is

$$A(t) \cos \left[24(\omega_C t - \phi_C) + s(t) \right] \tag{3}$$

where $A(t)$ is the signal-amplitude factor of the space-to-Earth signal at the ground station and $\phi_C = \omega_C/c \int_0^t \dot{R} \, dt$, radians, the doppler shift on ω_C. The significant waveform equations for the TRAC(E) receiving system are listed in Table 1. The numeral preceding each expression refers to the corresponding numerals in Fig. 1.

The system parameters which were used to achieve accurate tracking and communication with the Pioneer IV probe to lunar distances and farther are listed in Table 2. The 180 mw of transmitter power (± 0.5-db power tolerance)

was distributed between the carrier (96 mw) and the three telemetry carriers

so that accurate tracking and reliable data transmission could be realized to

at least 250,000 miles (lunar distance). Tolerances shown on the carrier

(± 0.3 db) and telemetry subcarriers (± 0.5 db) apply to permissible variations

in phase-modulation index (± 2 deg on each subcarrier). Examination of Table 2

shows that the received carrier signal level is -141.1 dbm when the lunar probe

is at a range of 250,000 miles. The resulting signal-to-noise ratios (S/N) in

the RF loop, AGC loop and angle-tracking loop are 8, 29.7, and 28.2 db

respectively. This provided sufficient margin in signal level to insure successful

tracking and communication. The significance of the bandwidths of the RF loop,

AGC loop, and angle-tracking loop shown in Table 2 are discussed in a later

section of this paper.

III. DESIGN OF TRACKING RECEIVER

The specifications for the TRAC(E) tracking receiver for <u>Pioneer III</u>

and <u>IV</u> are shown in the Appendix. Reference is made to the literature (Ref. 2,

5, 7-10) with regard to the development of these specifications. The 20-cps RF

phase-locked-loop noise bandwidth at threshold is determined by the stability

of the transmitter and receiver oscillators. As a consequence, the sensitivity

of the receiving system is limited by the threshold of the RF phase-locked loop.

With an effective noise temperature of 1435° K resulting from a receiver noise

figures of 7.5 db, an apparent antenna noise temperature of 42° K and a 0.7 db

loss for the simultaneous-lobing RF bridge and antenna transmission line to the

receiver input, the threshold of the receiver is -154.1 dbm. This assumes that the antenna is looking at a low-noise region of the sky.

The AGC system has a closed-loop noise bandwidth of 0.025 cps at receiver threshold. With this bandwidth, amplitude modulation, caused by the spinning probe and an unsymmetrical probe-antenna pattern, appears as a measurable error signal in the AGC loop. In addition, rms gain error is limited to 0.1 db at receiver threshold.

Gain and phase tracking in the angle-tracking receiver relative to the reference receiver is ±2 db and ±10 deg, respectively, for input signal levels from -45 dbm to threshold. Gain tracking maintains nearly constant gain in the hour-angle and declination servo systems. Phase tracking limits the shift of the electrical axis of the antenna system (due to phase shift) to ±0.01 angular mils (±0.0006 deg) for a 1-deg antenna-error-pattern s-curve with a 40-db null depth. The 0.06-cps closed-loop noise bandwidth for the angle-tracking servo system shown in Table 2 maintains rms angle jitter to 0.4 angular mils (0.022 deg) at receiver threshold.

IV.   DESCRIPTION OF EQUIPMENT

A.   Probe Transmitter

The transmitter for the Pioneer IV probe was located in the central 6-in.-diam well of the instrumented payload (Fig. 2). Figure 3 shows the flight transmitter mounted on the webbed platform that forms part of the payload structure and also supports the shutter experiment. Transistorized sub-assemblies are mounted on micarta discs, interposed between the webbing to

provide thermal isolation. The vacuum-tube cavity is fastened directly to the center web so that the whole payload becomes a heat sink for the vacuum tube. The over-all weight of the platform and transmitter is 1.33 lbs. The transmitter less platform weighs 0.98 lbs.

Circuit design was concentrated principally in the areas that would ensure early completion of a 960-Mc transmitter having the objective specifications outlined in Table 3. Some of the specialized components and their features that helped make an efficient 960-Mc lunar-probe transmitter possible are: (1) the Western Electric GF 45021 transistor, with its ability to operate efficiently at VHF frequencies (100 - 300 Mc) previously restricted to subminiature tubes; (2) the General Electric 7077, a subminiature ceramic UHF triode, which permitted the design of efficient subminiature UHF cavity amplifiers; (3) the Bell Telephone Laboratories "Varactor", a silicon-junction reactance diode developed for the U. S. Army Research and Development Laboratories, that operates as a frequency multiplier with considerably higher conversion efficiency than conventional diodes; (4) the ruggedized quartz crystal developed by the U. S. Army Signal Engineering Laboratories that enables phase-stable signals to be generated under conditions of extreme vibration; (5) the development of reliable voltage-sensitive capacitors which simplify the design of the phase-modulation circuits.

Semiconductor devices operating in circuits from 40 Mc to 960 Mc provided the RF signal drive to the vacuum-tube power-amplifier which furnished the RF excitation to the probe antenna. The objective specifications of the probe

transmitter (Table 3) were achieved in the Pioneer III and IV experiments. The

probe transmitter is described in detail in the literature (Ref. 11).

B.   Ground Tracking Receiver (Goldstone Station)

The RF portion of the TRAC(E) receiving system is mounted in an

electronics enclosure on the rear portion of the antenna reflector structure

(Fig. 5). The UHF portion of the reference, hour-angle, and declination-

angle receiver channels which include three preselector cavities, three balanced

mixers and three 30-Mc IF amplifiers, is housed in a weatherproof enclosure

(Fig. 5). The UHF portion of the local oscillator system which includes a X6

frequency multiplier, a three-way power divider, three UHF attenuators for

local oscillator drive adjustment, and a crystal-current meter circuit, is mounted

in a second weatherproof enclosure. Other weatherproof enclosures (Fig. 5)

contain power supplies and test equipment. The test equipment, which includes

UHF and VHF signal generators and a noise-figure test setup, facilitates

periodic checks of the receiver RF circuitry to insure optimum performance.

The amplified 30-Mc output signals from the reference, hour-angle, and

declination-angle channels are transmitted from the electronics enclosure

through coaxial cables to the receiver rack in the control building. The receiver

rack comprises three cabinets containing the remainder of the receiving system,

power supplies, and associated instrumentation (Fig. 6). The receiver system

can be operated with a closed-loop RF bandwidth of either 20 or 60 cps which

can be selected by means of a switch. Another switch permits selection of

either an 11-sec or a 300-sec time-constant filter for the AGC circuit. The mode used for the Pioneer IV experiment consisted of the 20-cps bandwidth and the 300-sec time constant for the AGC filter (Table 2).

Operational control of the tracking system during a tracking operation is provided at the control console (Fig. 7). Control of both the tracking receiver and the antenna servo system is provided at the console. In general, the receiver and servo systems each have three basic modes of operation: manual, automatic-track, and acquisition. In the acquisition mode, the tracking receiver and antenna search, in frequency and angle respectively, about the predicted frequency and angular position. Following acquisition, the received signal is automatically tracked in frequency and angular position (Ref. 12). Various receiver monitoring functions are provided at the control console.

V. PERFORMANCE DATA FOR PIONEER IV LUNAR PROBE

Following successful launching of the Pioneer IV lunar probe at 05:10:56 GMT on March 3, 1959, radio tracking was accomplished through launch, injection, and coasting flight by the three JPL-operated stations (Cape Canaveral, Puerto Rico and Goldstone) out to a maximum range of 652,000 km (about 407,000 miles). At this range, after 82 hours and 4 minutes of flight, a rapid decrease in signal level occurred as expected, due to loss of battery power. Prior to this event, received signal level was 5 db above threshold in a 20-cps bandwidth. After loss of signal during the fourth tracking period, a narrower bandwidth (10 cps) filter was installed in the tracking receiver, and the RF

carrier was tracked for about 9 additional minutes. Had the batteries lasted, tracking could have been accomplished to a range of 1,850,000 km (1,150,000 miles) using the 10-cps filter.

Performance of the TRAC(E) tracking and communication equipment was highly satisfactory during this experiment. Performance data for the Goldstone Station is presented in the following discussion.

A. Received Signal Level and Spin Modulation

The noise figures of the Goldstone receiver based on data taken March 1 and 3, 1959, were as follows:

Reference channel   7.5   db

Hour-angle channel 7.15 db

Declination channel 7.25 db

The measured noise figure of the reference channel agreed with the nominal value of 7.5 db. The theoretical receiving-system sensitivity based on unity signal-to-noise ratio in a 20-cps bandwidth, a receiver noise figure of 7.5 db (effective noise temperature 1355°K), an apparent antenna noise temperature of 42°K and a total loss of 0.7 db for the antenna simultaneous-lobing bridge and transmission line to the receiver input, is -154.1 dbm. The measured receiver sensitivity curve is shown in Fig. 8.

A comparison of measured with calculated signal level is shown in Fig. 9a for each tracking period for the Pioneer IV experiment. Throughout

the tracking operation the measured values are 3 to 5 db less than the calculated

curves (based on nominal values and assumed vehicle attitude).

After despin at 16:32:24 GMT on 3 March, the amplitude modulation of

the signal resulting from spin and precession occurred at frequencies of 0.23

cps and 0.046 cps with a maximum modulation depth of 3 to 3.5 db and a minimum

depth of 1 to 1.5 db. If the look angle between the spin axis and the line-of-sight

to the probe is assumed to be 80 deg with a precession angle of 10 deg, the

antenna pattern measurements agree with the observed depth of spin modulation,

and the average signal strength comparison would appear as shown in Fig. 9b

for the first tracking period.

The received signal levels were determined by measuring the AGC voltage

with a digital voltmeter and converting this to signal level, using the receiver-

sensitivity curve (Fig. 8). The measured values are indicated by the symbols

in Fig. 9. In general, the slopes of the measured curves are slightly greater

than the expected slopes. The signal level at acquisition, the signal level at the

end of each track period, and the changes in level for each period are shown in

Table 4. The estimated uncertainty of ±1.5 db in the measured data is based

upon the following:

Receiver sensitivity error   ±1   db

Recording, calibration, and data reduction errors   ±0.5 db

In Fig. 9 the expected signal level is shown for comparison with the

measured data. The solid line represents the signal level calculated on the

basis of the following:

Transmitted carrier power	22. 1 dbm
Vehicle antenna gain	function of look angle (Figure 10)
Ground antenna gain	41. 1 db (indirect measurement)
Space attenuation, db	$92.1 + 20 \log_{10}$ (Range in kilometers)

The look angle is calculated on the assumption that the spin axis of the probe is essentially co-linear with the velocity vector at injection (look angle varies from 45. 5 to 56. 2 deg for the experiment). The vehicle antenna pattern of Fig. 10 is based upon the measurements of antenna gain as a function of look angle and rotation of the antenna. The solid curve which was used for calculating signal level represents the geometric mean of the gain for full rotation at the given look angle. The dashed curves show the maximum and minimum gain and indicates the degree of amplitude modulation to be expected at each given look angle. The uncertainty of the calculated data is based upon the following:

Ground-antenna gain (variation due to polarization)	$\left.\begin{array}{r}-1.7\\+0.1\end{array}\right\}$ db
Ground-antenna gain (uncertainty)	$+1$ db
Transmitter power	± 0.5 db
Vehicle-antenna gain	± 1.0 db

This gives a total uncertainty in the calculated data of $\left.\begin{array}{r}-4.2\\+2.6\end{array}\right\}$ db

The measured signal levels are less than the expected values by 3 to 5 db. While the regions of uncertainty of the calculated and observed data overlap slightly, it is believed that the difference between expected and measured values

is of the order of 3 db. This apparent loss of signal can be explained by assuming a look angle of the order of 80 deg.

B. Angle Tracking System

The reduction of tracking data was essentially a problem of filtering, by statistical analysis, the random observational errors and the systematic bias errors. The computational program for generating the Pioneer IV trajectory is described in detail in a JPL External Publication (Ref. 12). The trajectory angles were corrected for atmospheric refraction and all known mechanical sources of error, then the angles were compared with unsmoothed raw data for the last day of tracking (March 6, 1959). The hour-angle errors for this period ranged from +0.035 deg to -0.11 deg. Near threshold the hour-angle errors were +0.02 deg to -0.1 deg. Using smoothed values of observed data the hour angle error was about -0.03 deg at the system threshold. The declination errors for the same period ranged from +0.07 deg to -0.04 deg. Using smoothed values of observed data the declination error was about 0.02 deg at threshold. As indicated in an earlier portion of this paper, calculated rms angle jitter at system threshold is 0.4 mils which generally agrees with measured values.

VI. FUTURE PLANS FOR IMPROVEMENT

Extraterrestrial radio communication has been demonstrated and practiced successfully by radio astronomers for many years. As a result of their pioneering effort, the problems associated with communicating with rocket-launched space probes have been and will continue to be less difficult.

Utilization of their data, analyses, techniques and in some cases actual

equipment designs made it possible to develop the TRAC(E) system in a very

short period of time with sufficient long-term capabilities that it could

communicate to the distance of the Moon in 1958 and to the planets during

the period 1960 to 1962 (see Table 5). A basic element of the TRAC(E) system,

for example, is the 85-ft-diam.antenna designed for radio astronomy research

by the Blaw-Knox Company under an Associated Universities contract. With

this antenna and the TRAC(E) receiver described in this report it would be

possible to communicate to the nearby planets. However, future plans are to

extend the range (and/or the bandwidth) still further by the addition of low-noise

amplifiers. An overall noise temperature of 400°K is predicted for 1960, using

a parametric amplifier, and a temperature of 40°K for 1962, using a Maser.

The real significance of Table 5 is that the principal factors which are

expected to extend the communicating range are related to the space vehicle.

Over a period of four years, it is suggested that the vehicle transmitter power

could be increased 27 db, from 200 mw to 100 w, and the vehicle-antenna gain

could be increased 36 db. With these improvements Table 5 shows that space

communications could be maintained anywhere in the solar system with a band-

width of 30 cps. Solution of these problems in the time scale indicated depends

on many factors, such as launching vehicle reliability, payload weight, primary

power, Earth-seeking vehicle antenna system, financial support, etc.

The present TRAC(E) system is a one-way link which measures two

angles and one-way Doppler and receives telemetry. Future TRAC(E)

communications will be two-way, employing a 10-kw UHF ground transmitter and a vehicle-borne transponder. The two-way TRAC(E) system will measure two angles, range and range-rate; it will receive telemetry and also provide a radio command link to the space vehicle.

Table 1. Waveform Equations for the TRAC(E) Receiving System

(1) $A(t) \cos [24\omega_c t + s(t)]$

(2) $g_\Sigma(\alpha) A(t) \cos [24(\omega_c t - \phi_c) + s(t)]$

(3) $\sin 24(\phi_c^* - \phi_c) \approx 24(\phi_c^* - \phi_c)$

(4) $\cos \dfrac{31 \times 3}{30 \times 4} (\omega_c t - \phi_c^*)$

(5) $\cos \dfrac{31 \times 3}{30 \times 4} \phi_c^* = \cos \left[\dfrac{31 \times 3}{30 \times 4}\right] \dfrac{\omega_c}{c} \int_0^t \dot{R}\, dt$

(6) $g_\Delta(\alpha) A(t) \cos [24(\omega_c t - \phi_c) + s(t)]$

(7) $E \dfrac{A(t)}{A^*(t)} \dfrac{g_\Delta(\alpha)}{g_\Sigma(\alpha)} \approx \dfrac{A(t)}{A^*(t)} g_\Delta'(0)$

$A(t)$ = signal amplitude factor of the signal radiated from the probe

E = dc reference in the receiver AGC loop

c = velocity of propagation, meters/sec

f_1 = measured frequency of the 31 mc doppler reference

f_{c_0} = probe transmitter oscillator frequency with zero doppler

f_d = measured frequency at the output of the doppler phase detector

$g_\Sigma(\alpha)$ = voltage pattern of the main-beam antenna normalized so that $g_\Sigma(0) = 1$

$g_\Delta(\alpha)$ = voltage pattern of the split-beam antenna normalized with respect to $g_\Sigma(0)$

$g_\Delta'(0)$ = slope of the $g_\Delta(\alpha)$ curve near $\alpha = 0$, mils^{-1}

$s(t)$ = telemetry phase modulation

t = time, seconds

$\dot{R}$ = radial component of probe velocity meters/sec
$= c \left[1 - \dfrac{960}{31 f_c} (f_d + f_1)\right]$

α = tracking error of the antenna servo, mils

ϕ_c = doppler phase shift on $\omega_c = \dfrac{\omega_c}{c} \int_0^t \dot{R}\, dt$, radians

ω_c = angular frequency of the probe transmitter oscillator = 2π (40.0021 mc) rad/sec

$\dfrac{1}{A^*(t)}$ = a measure of the voltage gain of the ground receiver so defined that the incoming signal $A(t)$ multiplied by the receiver gain figure $1/A^*(t)$ equals unity

Table 2. TRAC(E) System Characteristics for <u>Pioneer III</u> and <u>IV</u>

Transmitter power, total (at 250,000 miles)	180 mw	±20 mw
	+22.5 dbm	±0.5 db
Vehicle antenna gain	2.5 db	±1 db
Carrier power	96 mw	±7 mw
	+19.8 dbm	±0.3 db
Subcarrier power, Ch. 1	14 mw	1.5 mw
	+11.5 dbm	±0.5 db
Subcarrier power, Ch. 2	14 mw	1.5 mw
	+11.5 dbm	±0.5 db
Subcarrier power, Ch. 3	36 mw	+4 mw
	+15.5 dbm	±0.5 db
Space loss at 250,000 miles	204.5 db	
Ground-antenna gain	41.8 db	
Transmission-line loss	0.7 db	
Receiver noise figure	7.5 db	
Receiver bandwidth $(2B_{L_o})$	20 cps	
Receiver threshold	-154.1 dbm	
Angle-track loop bandwidth $(2B_L)$	0.06 cps	
Angle-track loop receiver threshold	-179.3 dbm	
AGC loop bandwidth $(2B_{L_o})$ at threshold	0.025 cps	
AGC loop threshold	-183.1 dbm	

Table 2 (Cont'd)

At 250,000 Miles

      Received RF signal level . . . .   -141.1 dbm

      S/N for RF loop . . . .   8.0 db

      S/N for AGC loop . . . .   39.7 db

      S/N for angle-tracking loop . . . .   38.2 db

Table 3. Probe Transmitter Objective Specifications

Carrier frequency (nominal)	960	Mc
Output power	180	mw
Crystal oscillator frequency (nominal)	40	Mc
Short-term frequency stability (15 minutes)	1	part/10^7
Long-term frequency stability	1	part/10^6
Power output stability	±1/2	db
Maximum incidental phase modulation	2	deg/g
Total weight	0.9	lb
Over-all size (6 in. diam. x 1 in. high)	28	in.^{3}
Primary power input	2.4	watts
Operating time with 6.5-lb battery	120	hr
Transmitter efficiency, exclusive of antenna gain	7.5	%

Table 4. Range and Signal-Level Data for <u>Pioneer IV</u>

Tracking Period No.	Date	Time GMT	Range Km	Signal Level at Acquisition dbm	Signal Level at Loss of Lock dbm	Change of Signal Level (Neglecting horizon effect)	
						Measured db	Expected db
1	3/3/59	11:47:00 to 21:05:48	97,400 to 194,000	-144.5	-154.5	7.5	6.1
2	3/4/59	12:33:54 to 21:15:53	315,000 to 380,000	-141.5	-154.0	2.5	1.7
3	3/5/59	12:34:52 to 21:18:46	487,000 to 545,000	-147.5	-156.5	2.0	1.0
4	3/6/59	12:50:00 to 15:16:19	644,000 to 657,000	-150.5	-156.2	0.7	0.2

Table 5. Long-Term System Capabilities

Characteristic	Capability, by Date		
	1958	1960	1962
Transmitter Power, watts	0.2	10	100
Vehicle Antenna Gain, db	0	16	36
Receiver Sensitivity:			
Noise temperature, °K	2000	400	40
Bandwidth, cps	30	30	30
Earth-vehicle range for 10 db S/N, miles	4×10^5	4×10^7	4×10^9

Fig. 1. Functional Block Diagram, Pioneer IV Transmitter and Goldstone TRAC(E) System
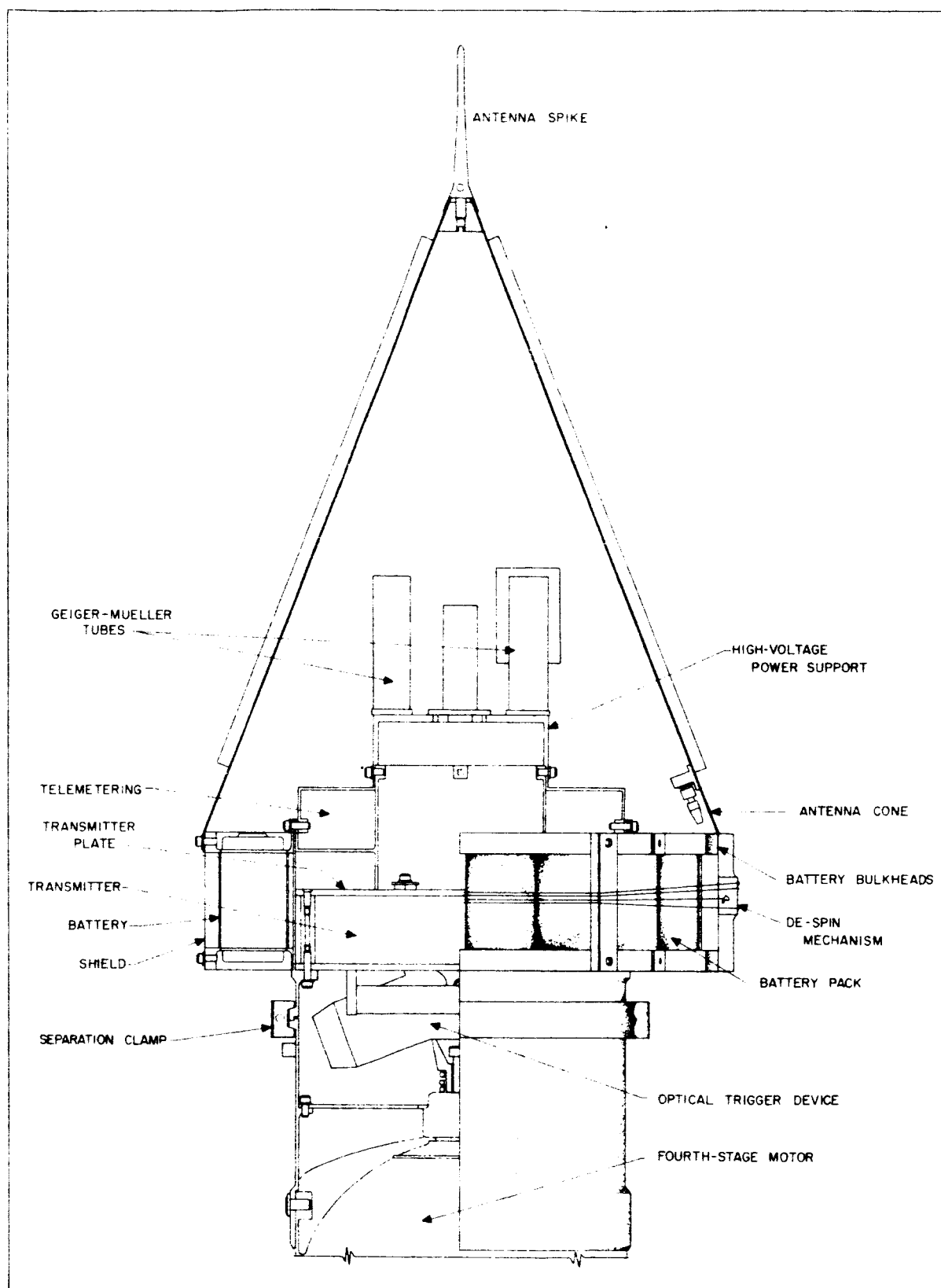
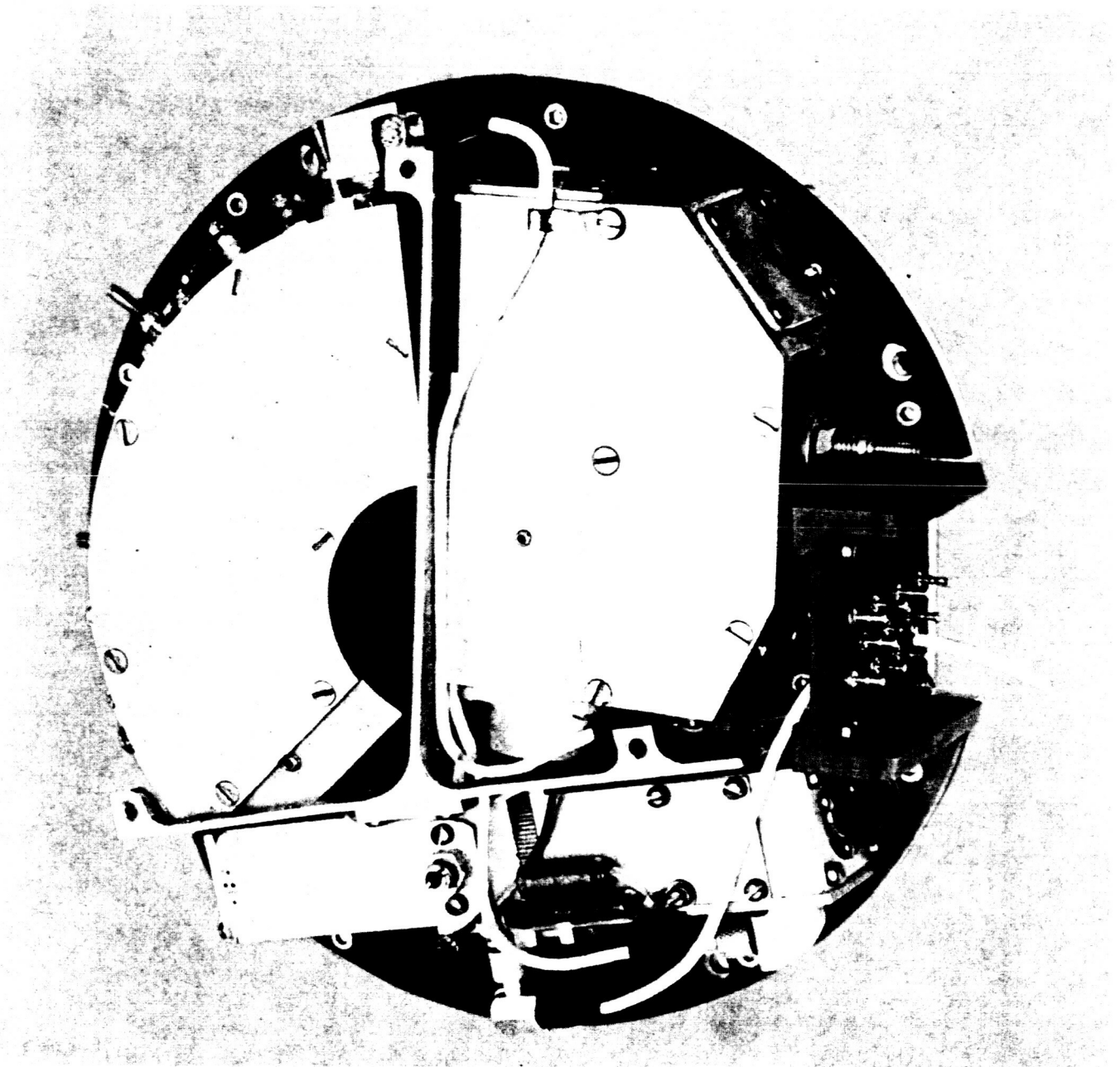Fig. 2.   Pioneer IV Instrumented Payload

Fig. 3.   Probe Transmitter Mounted on Webbed Platform

CONTROL BUILDING

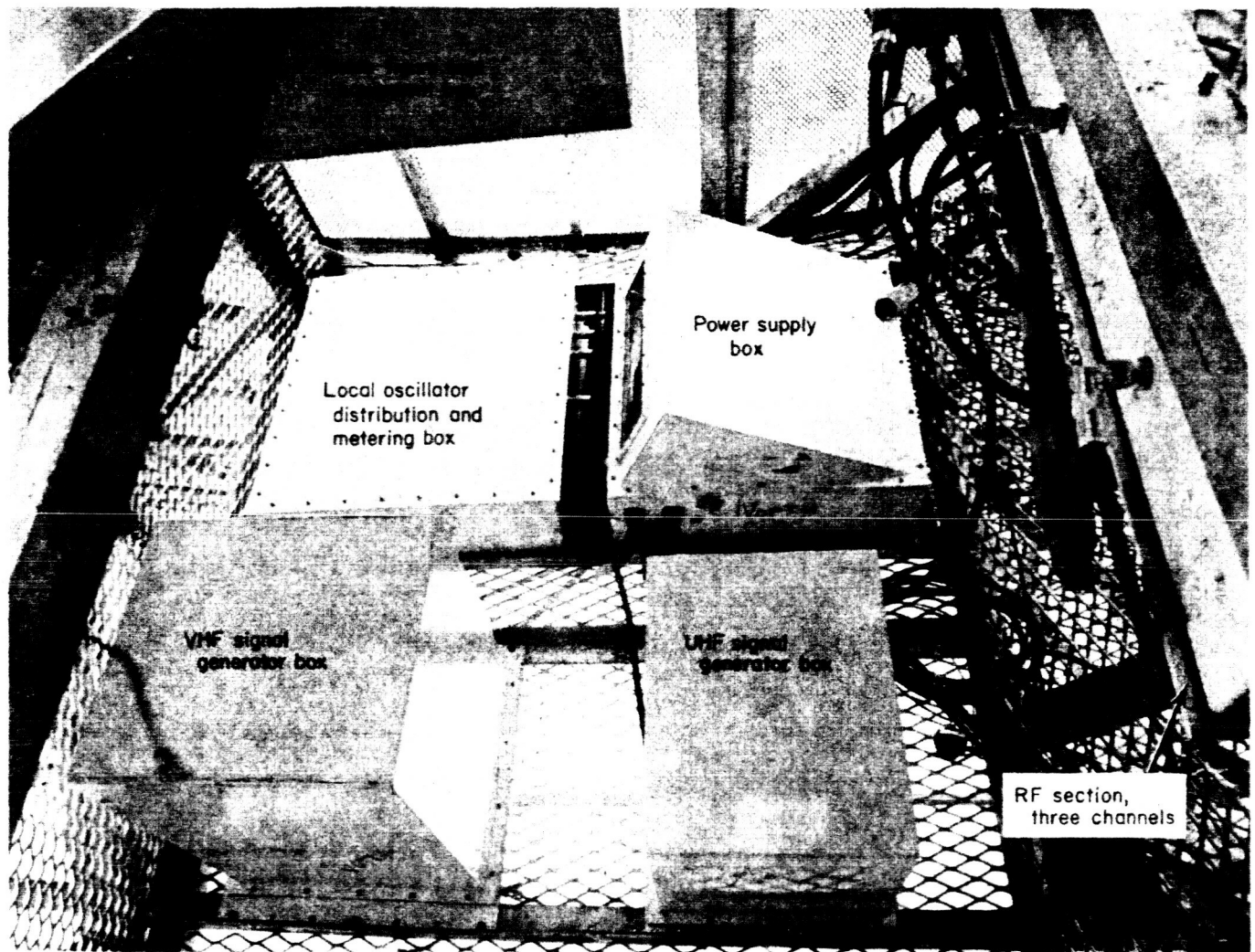Fig. 4. Goldstone Tracking Station
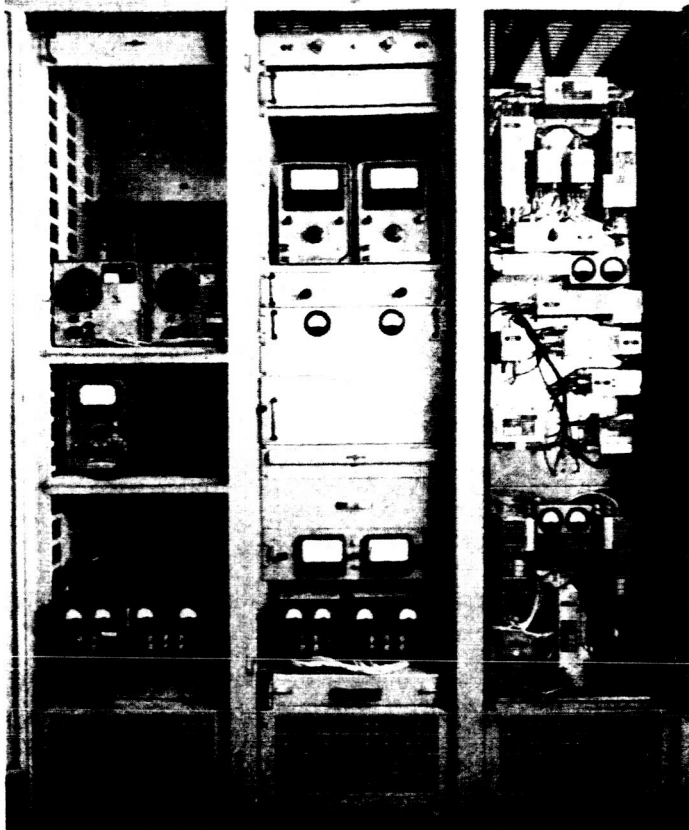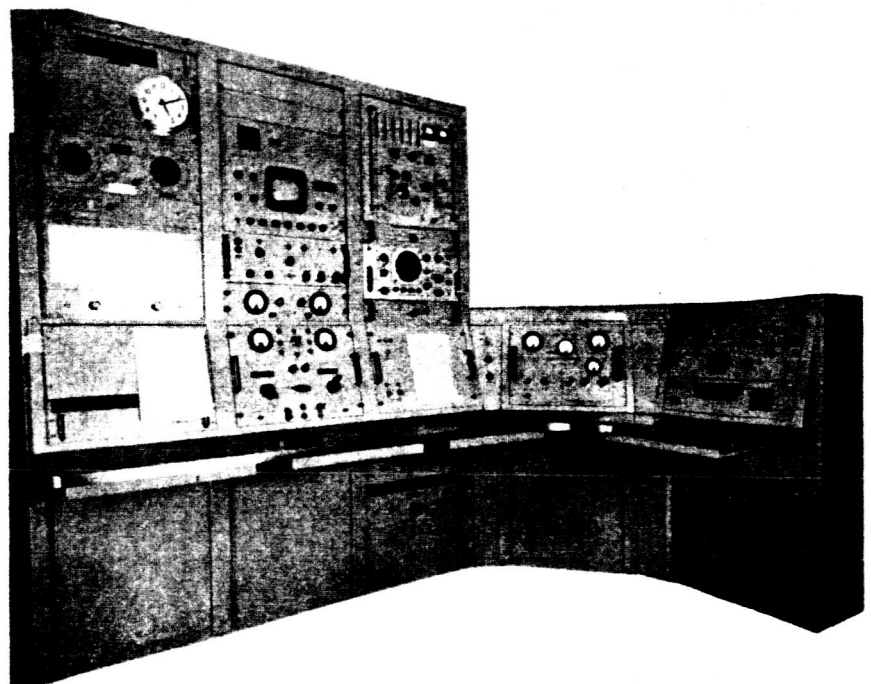
Fig. 5. Electronic Enclosure
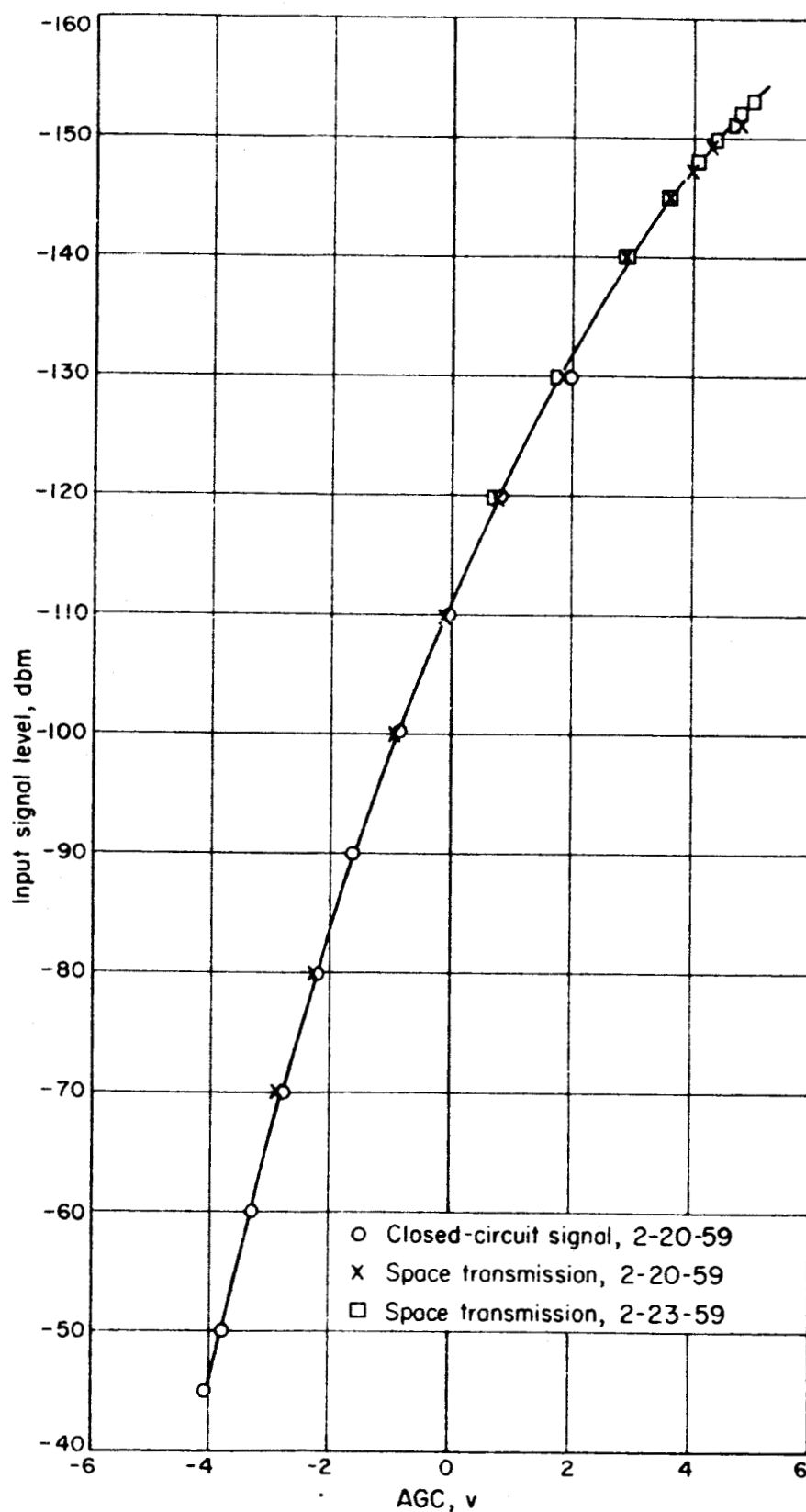
Fig. 6.   Receiver Rack

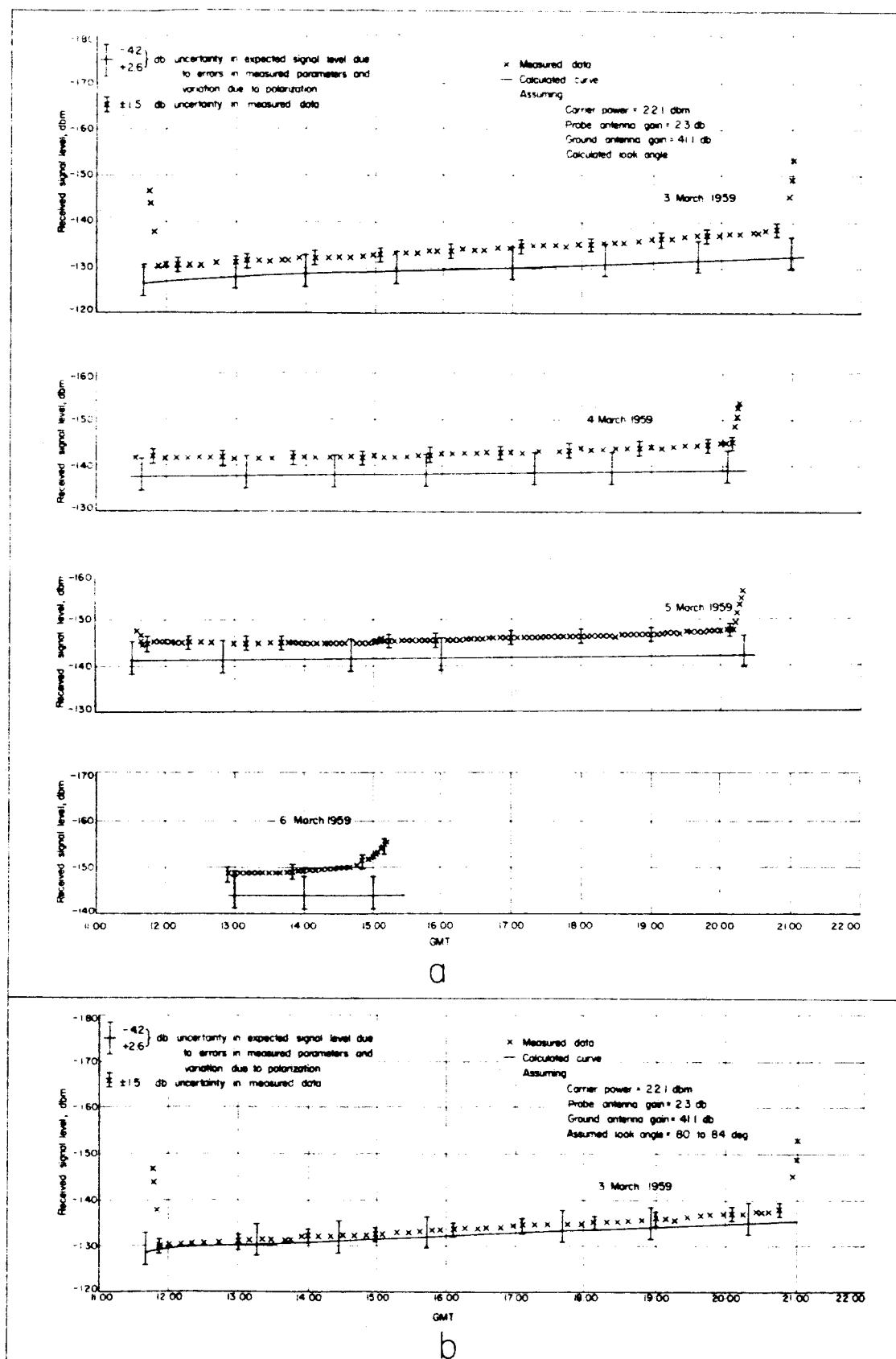Fig. 7.   Control Console

Fig. 8.   Receiver Sensitivity

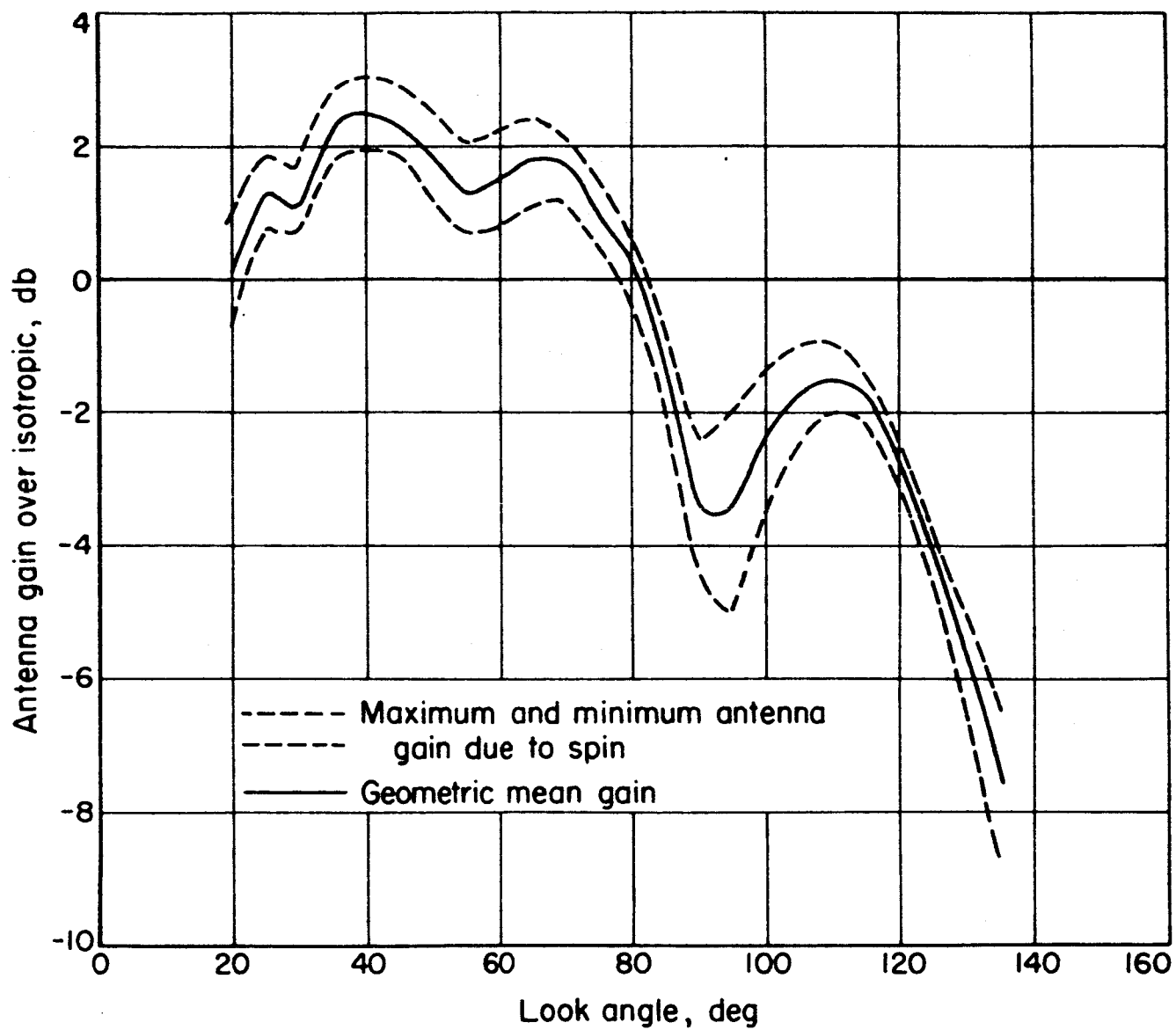Fig. 9. Measured and Calculated Values of Received Signal Level

Fig. 10. Vehicle Antenna Pattern

REFERENCES

1. Linnes, K. W., R. D. Merrick, and R. Stevens. "Ground Antennas for Space Communication Systems," to be published in IRE Transactions on Space Electronics and Telemetry.

2. Rechtin, E., "The Design of Optimum Linear Systems," External Publication No. 204, Jet Propulsion Laboratory, Pasadena, Calif., April 1953.

3. Jaffe, R., and E. Rechtin, "Design and Performance of Phase-Lock Circuits Capable of Near Optimum Performance Over a Wide Range of Input Signal and Noise Levels," IRE Transactions on Information Theory, Vol. IT-1, pp. 66-76 (March 1955); External Publication No. 263, Jet Propulsion Laboratory, Pasadena, Calif., 22 December 1954.

4. Gilchriest, C. E., "Application of the Phase-Locked Loop to Telemetry as a Discriminator on Tracking Filter," IRE Transactions on Telemetry and Remote Control, Vol. TRC-4 No. 1, pp. 20-35 (June 1958); External Publication No. 386, Jet Propulsion Laboratory, Pasadena, Calif., 15 April 1957.

5. Margolis, S. G., "The Response of a Phase-Locked Loop to a Sinusoid Plus Noise," IRE Transactions on Information Theory, Vol. IT-3, No. 1, pp. 136-144 (March 1957).

6. Richter, H. L., R. Stevens, and W. F. Sampson. "A Minimum-Weight Instrumentation System for a Satellite," presented at National Telemetry Conference, 27-29 May 1957; External Publication No. 376, Jet Propulsion Laboratory, Pasadena, Calif., 23 May 1957.

7. Victor, W. K. "The Evaluation of Phase-Stable Oscillators for Coherent Communication Systems," presented at 10th Frequency Control Symposium, Signal Research and Development Laboratory, May 1956; External Publication No. 337, Jet Propulsion Laboratory, Pasadena, Calif., 8 May 1956.

8. Viterbi, A. J. "Design Techniques for Deep-Space Television," Journal of the British Institution of Radio Engineers, Vol. 19, No. 4 (September 1959); External Publication No. 623, Jet Propulsion Laboratory, Pasadena, Calif., 13 April 1959.

9. Davenport, W. B., Jr. "Signal-to-Noise Ratios in Band-Pass Limiters," Journal of Applied Physics, Vol. 24, No. 6, pp. 720-7 (June 1953).

REFERENCES (Cont'd)

10. Victor, W. K., and M. H. Brockman. "The Application of Linear Servo Theory to the Design of AGC Loops," Proceedings of the IRE, Vol. 48, No. 2, pp.234-8; External Publication No. 586, Jet Propulsion Laboratory, Pasadena, Calif., 22 December 1958.

11. Malling, L. R. "A 960 Mc Lunar Transmitter," Astronautics, Vol. 4, No. 5, pp.29-39 and 104 (May 1959); External Publication No. 596, Jet Propulsion Laboratory, Pasadena, Calif., 7 January 1959.

12. Eimer, M., and R. Stevens. "Tracking and Data Handling for the Pioneer III and Pioneer IV Firings," External Publication No. 701, Jet Propulsion Laboratory, Pasadena, Calif., 14 August 1959.

APPENDIX A

Design Specifications of TRAC(E) Tracking Receiver
for <u>Pioneer III</u> and <u>IV</u>

1. Frequency: nominal 960.05 Mc (also see 12.)

2. Noise Figure: 7.5 db or less

3. Bandwidth: 20 cps at threshold

4. Threshold: -154.1 dbm defined as the signal level at which the receiver loses lock

5. Range of Input Signal Level: -45 dbm to threshold

6. R-f Loop Characteristics:

    a. RF-loop Transfer Function

$$(1 + 3s/4B_L)/(1 + 3s/4B_L + 9s^2/32B_L{}^2)$$

where

$$2B_L = (1/2\pi) \int_{-\infty}^{+\infty} \left| H(j\omega) \right|^2 \, d\omega$$

$$= (2/3) \, B_{L_0} \, (1 + 2\alpha/\alpha_0)$$

and

$$2B_{L_0} = 2(9G_0/32\tau_1)^{1/2}$$

$$\tau_1 = R_1 C$$

G_0 = open-loop gain at threshold
$= 360 \times 30 \times k_m \times k_{vco} \times \alpha_0$

k_m = sensitivity of the RF phase detector

= 0.7 volt/deg

k_{vco} = sensitivity of the RF VCO

= 250 cps/volt

α_0 = signal suppression factor at threshold

= 0.088 for 20-cps bandwidth

$$\alpha = \left[1 + antilog_{10} \ (1 + P_N - P_S)/10\right]^{-1/2} = \left[1 + antilog_{10} \ (1 - 134.1 - P_S)/10\right]^{-1/2}$$

where P_N = available noise power in the 2-Kc passband of the 455-Kc IF amplifier = $log_{10} \ (k \ T_{eff} \ \Delta f \ 10^3)$ = -134.1 dbm, P_S = available signal power in the same 2-Kc bandwidth in the same units as P_N, and k = Boltzmann's constant, 1.37×10^{-23} joules/°K.

Consequently

$$H(s) = (1 + s/\lambda)/(1 + s/\lambda + s^2/2\lambda^2)$$

where

$$\lambda = (4B_{L_0}/9)\left\{1 + 2/\alpha_0 \ \left[1 + antilog_{10} \ (1 - 134.1 - P_S)/10\right]\right\}^{1/2}$$

b. RF-Loop Noise Bandwidth:

(1) Design Value at Design Threshold and Signal Frequency: $2B_{L_0}$ = 20 cps.

(2) Variation with Signal Level: The RF-loop noise bandwidth shall vary from 20 cps at design threshold to 158 cps at strong signal levels (α = 1).

(3) Variation with Signal Frequency: The threshold RF-loop noise bandwidth shall vary from 20 cps at design signal frequency to not less than 14.1 cps at signal frequencies displaced ±2.6 parts in 10^5 from the deisgn signal frequency.

c. RF-Loop Phase Error:

  (1) Variation with Signal Input Frequency: The static phase error at threshold shall not exceed 6 deg at signal frequencies displaced ±2.75 parts in 10^6 from the design signal frequency. At these two frequency extremes, the threshold will be reduced 1 db from that specified at design signal frequency. Static phase error at strong signal levels ($\alpha = 1$) shall not exceed 13.5 deg at signal frequencies displaced ±2.6 parts in 10^5 from the design signal frequency.

  (2) **Maximum Rate of Change of Input Signal Frequency:** The phase error at threshold shall not exceed 6 deg for a maximum rate of change of 6 parts in 10^9 per second in input signal frequency. At this maximum rate, the threshold will be reduced 1 db relative to that obtained for a zero rate of change in signal frequency. The phase error at strong signals ($\alpha = 1$) shall not exceed 30 deg for a maximum rate of change of 3.5 parts in 10^7 per second in input signal frequency.

  (3) rms Phase Error: The rms phase error due to noise shall not exceed 1.0 radian at design threshold; it shall not exceed 0.06 radian at an input signal level of -120 dbm.

  (4) Residual Phase Error: The residual phase error shall not exceed 3 deg (peak) at strong signal levels ($\alpha = 1$) within an RF-loop noise bandwidth of 20 cps.

  (5) Noise Bias: The maximum phase error due to noise at threshold shall not exceed 1% of the phase-detector s-curve amplitude at threshold (equivalent to static phase error of 0.6 deg).

7. AGC-Loop Characteristics (Coherent AGC)

  a. AGC-Loop Transfer Function:

$$H(s) = \left[(1 + 1/G) + (\tau/G)s \right]^{-1}$$

where

   τ = time constant of AGC filter = 300 sec

   G = AGC-loop gain = $K_D K_A$

  and K_D = AGC-detector constant,

    = 3.1 v/db at threshold

= 4.0 v/db at -45 dbm input signal level

K_A = constant associated with the gain of the receiver

= 5 db/v at threshold

= 17 db/v at -45 dbm input signal level

b.   AGC-Loop Noise Bandwidth:

(1)   Design Value at Design Threshold:

$$2B_L = 0.025 \text{ cps}$$

(2)   Variation with Signal Level: The AGC loop noise bandwidth shall vary from 0.025 cps at design threshold to 0.11 cps at an input signal level of -45 dbm.

c.   AGC Loop Gain Error:

(1)   Static Gain Error: The variation in coherent detected receiver output shall vary not more than 6 db for the range of input signal levels from -45 dbm to threshold.

(2)   Maximum Rate of Change of Input Signal Level: The gain error at threshold shall not exceed 1 db for a maximum rate of change of 0.05 db per second in input signal level.

The gain error at an input signal level of -45 dbm shall not exceed 1 db for a maximum rate of 0.25 db per second in input signal level.

(3)   rms Gain Error: rms gain error introduced in the RF and angle tracking loops at threshold shall not exceed 0.1 db rms; rms gain error at an input signal level of -120 dbm shall not exceed 0.003 db rms.

8.   30/31-Mc Frequency-Shifter Phase-Locked-Loop Characteristics:

a.   Frequency-Shifter Loop Transfer Function:

$$H(S) = (1 + 3s/4B_L)/(1 + 3s/4B_L + 9s^2/32B_L^2)$$

where

$$2B_L = 2(9G/32\tau_1)^{1/2}$$

$$\tau_1 = R_1C$$

$$G = (360)(32)\, k_m k_{vco}$$

$$k_m = \text{Sensitivity of frequency-shifter phase detector}$$

$$= 0.25 \text{ v/deg}$$

$$k_{VCO} = \text{Sensitivity of the frequency-shifter VCO}$$

$$= 45 \text{ cps/volt}$$

    b.   Frequency-Shifter Loop Noise Bandwidth:

        (1) Design Value at Design Frequency:

$$2B_L = 1340 \text{ cps}$$

        (2) Variation with Frequency: The frequency-shifter loop noise bandwidth shall vary from 1340 cps at design frequency to not less than 950 cps at frequencies displaced ± 3 parts in 10^5 from the design frequency.

        c.   Frequency-Shifter Loop Phase Error: The static phase error shall not exceed 5 deg at frequencies displaced ± 3 parts in 10^5 from the design frequency.

9.   30.455 Mc SSB-Modulator Phase-Locked-Loop Characteristics:

    a.   SSB Modulator Loop Transfer Function:

$$H(s) = (1 + 3s/4B_L)/(1 + 3s/4B_L + 9s^2/32B_L^2)$$

where

$$2B_L = 2(9G/32\tau_1)^{1/2}$$

$$\tau_1 = R_1C$$

$$G = 360 k_m k_{vco}$$

k_m = sensitivity of SSB-modulator phase detector

= 0.7 v/deg

k_{vco} = sensitivity of the SSB-modulator VCO

= 250 cps/volt

    b. SSB-Modulator Loop Noise Bandwidth:

        (1) Design Value at Design Frequency:

$$2B_L = 1200 \text{ cps}$$

        (2) Variation with Frequency: The SSB-modulator loop noise bandwidth shall vary from 1200 cps at design frequency to not less than 850 cps at frequencies displaced ±3 parts in 10^5 from the design frequency.

    c. SSB-Modulator Loop Phase Error: The static phase error shall not exceed 10 deg at frequencies displaced ±3 parts in 10^5 from the design frequency.

10. Angle-Error Channel Characteristics:

    a. Gain Tracking: The differential gain between either angle-error channel and the reference channel shall not exceed 2 db over the range of input-signal levels from -45 dbm to threshold. Gain tracking is determined by comparison of the coherent output-signal levels in the angle-error channel to the reference-channel output.

    b. Phase Tracking: The differential phase between either angle-error channel and the reference channel shall not exceed ±10 deg over the range of input-signal levels from -45 dbm to threshold. Phase tracking is determined by comparison of the phase of the coherent output-signal level in the angle-error channel to reference-channel phase output.

    c. rms Angle Tracking Error: rms angle tracking error in the 0.06-cps noise bandwidth of the angle-tracking servo system shall not exceed 0.022 deg rms at threshold.

11. Modulation Characteristics:

Amplitude Response and Phase Symmetry of a 2-Kc Passband: The amplitude characteristic of the 455-Kc IF amplifier shall be flat to ±1.5 db within the 2-Kc passband.

The phase characteristic of the 455-Kc IF amplifier shall be symmetrical to within 45 deg about the center of the 2-Kc passband.

12. Frequency:

The nominal center frequency shall be 960.05 Mc with the ability to track plus or minus 3.0 parts in 10^5 from the nominal center frequency. By changing the crystal and retuning the VCC, the center frequency can be changed between 955 Mc and 965 Mc.

13. Input VSWR:

The input VSWR to the receiver shall be less than 1.5 to 1 for a 50-ohm transmission line.

14. Image Rejection:

The image rejection of the receiver shall be at least 40 db.

15. Telemetry Bandwidth:

The narrowest bandwidth of the receiver before the telemetry output shall be 2 Kc.

16. Residual Phase Modulation:

The residual phase modulation in the RF loop when measured with a signal source at -60 dbm shall be less than 3 deg (peak).

17. Internal Interference in the RF Loop:

The internal interference in the RF loop due to coherent leakage signals of the receiver shall be at least 40 db below the signal level at threshold when the interference enters ahead of the limiter and at least 60 db below the signal level at threshold when the interference enters following the limiter.

18. Internal Interference in the AGC Loop:

The internal interference in the AGC loop due to coherent leakage signals of the receiver shall be at least 40 db below the signal level at threshold.

19. Internal Interference in the Angle-Error Channels:

The internal interference in the angle-error channels due to coherent leakage signals of the receiver shall be at least 40 db below the signal level at threshold.

20. Cross Coupling Between Channels:

The signal isolation between any two channels shall be at least 60 db.

21. Receiver IF Frequencies:

The receiver IF frequencies shall be 30 Mc and 455 Kc.

22. First Local-Oscillator Frequency:

The first local-oscillator signal shall be derived from a 31-Mc VCO which is frequency multiplied by 30.

23. Coherent Local-Oscillator Frequencies:

The local-oscillator signals shall be derived in such a manner that the received signal frequency can be determined by measurement of the 31-Mc VCO frequency only.

24. Recording Outputs:

Provision shall be made for making the following available for recording:

Receiver AGC

RF-loop dynamic phase error and telemetry

Telemetry subcarriers

Doppler frequency plus constant frequency

Spin modulation

Declination error

Hour-angle error